Carpacio: Repurposing Capacitive Sensors to Distinguish Driver and Passenger Touches on In-Vehicle Screens

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ABSTRACT

Standard vehicle infotainment systems often include touch screens that allow the driver to control their mobile phone, navigation, audio, and vehicle configurations. For the driver's safety, these interfaces are often disabled or simplified while the car is in motion. Although this reduced functionality aids in reducing distraction for the driver, it also disrupts the usability of infotainment systems for passengers. Current infotainment systems are unaware of the seating position of their user and hence, cannot adapt. We present *Carpacio*, a system that takes advantage of the capacitive coupling created between the touchscreen and the electrode present in the seat when the user touches the capacitive screen. Using this capacitive coupling phenomenon, a car infotainment system can intelligently distinguish who is interacting with the screen seamlessly, and adjust its user interface accordingly. Manufacturers can easily incorporate Carpacio into vehicles since the included seat occupancy detection sensor or seat heating coils can be used as the seat electrode. We evaluated Carpacio in eight different cars and five mobile devices and found that it correctly detected over 2600 touches with an accuracy of 99.4%.

Author Keywords

Driver detection; Vehicle infotainment; Capacitive sensing; Touch; Driver assistance

ACM Classification Keywords

H.5.2. [User Interfaces] – Input devices and strategies

INTRODUCTION

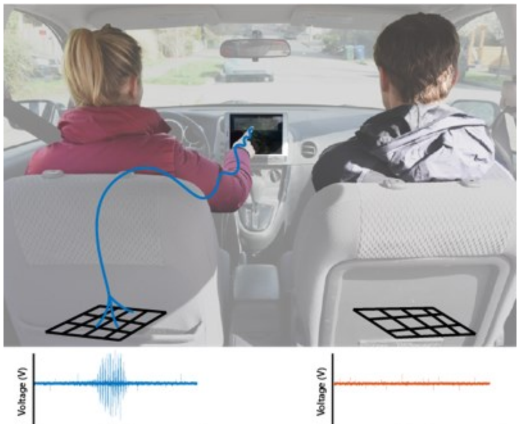

Figure 1: Carpacio is a system that differentiates whether a driver or passenger touches the screen in a car by measuring the parasitically coupled signal from the screen.

Infotainment systems are standard in most modern cars. To minimize driver distraction due to these infotainment systems, auto manufacturers often require stopping the car before a driver or passenger can access the full set of features. Thus, drivers may turn to their smartphones in place of infotainment systems, which exacerbates the driver distraction problem and renders the in-car infotainment system useless. With the ability to sense whether the driver or passenger is interacting with the infotainment system, automakers can introduce adaptive user interfaces that are limited and simple for the driver, but fully functional for passengers.

In this paper, we present *Carpacio*, a capacitive coupling-based system that discriminates who is touching the screen by taking advantage of the existing touch screen sensing system. A standard capacitive touch screen relies on sensing the changes in mutual or self-capacitance when a finger touches the screen. A side effect of the capacitive sensing screen is that when touched by an object that shares common ground, some of that electric field is absorbed by the object. This absorbed electric field is then grounded through the object. By placing an electrode between the object and the ground, this coupled signal can be measured. In a vehicle, an electrode could be inserted in each seat of the vehicle, or already existing seat hardware could be repurposed. When a touch occurs on the capacitive touch

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screen, Carpacio can identify the touch source based on which seat received the electric signal. In modern vehicles, these electrodes can either be created by simply adding an ADC to the heating coils in the car seats or reusing the sensing system of occupancy-detection systems in car seats. User discrimination through this parasitic capacitive coupling has been demonstrated by Dietz et al. in DiamondTouch [6], where an electrode is instrumented on each seat to discriminate who is touching the touch screen. In their follow-up work DT Controls [5], Dietz et al. further extends the DiamondTouch concept towards in-vehicle user identification. They illustrate how to integrate DiamondTouch into a car by injecting a unique signal into a touch screen to be sensed by the electrode instrumented on the sensors embedded in the seat of the user to distinguish between the driver and the passenger during screen usage. Our work extends upon DiamondTouch and DT Controls by utilizing the existing infrastructure in a car environment to recreate the functionality described in DT Controls by using the existing signals generated by devices in the screen. This includes using a variety of unmodified touch screens, smartphones, and capacitive based console controllers (Figure 2). By developing a working system using the existing infrastructure in a car, our work quantitatively validates the robustness and practicality of the concepts illustrated in DT Controls. Furthermore, our paper explores several practical aspects of this technology, such as real-world testing, signal processing considerations of extraneous noises existing in present day vehicles, and an evaluation of various types of capacitive sources found in the real world.

Figure 2: Built-in vehicle touch screen (Left), capacitive based console controller (Middle), smartphone (Right)

A validation study was conducted on a set of eight vehicles with capacitive infotainment interfaces, including two with capacitive touch console remotes as used in some of the Mercedes Benz and Mini vehicles, and five phone/tablet devices. In the study, two users touched the screen at a randomized alternating sequence, with 100 touches per user for each screen, divided into an equal number of taps, tap-and-hold, swipes, and multi-touch hold; giving a total of 200 touch interactions per screen. We included a variety of touch types to test Carpacio's performance at detecting different duration and contacts of touches, but did not try to classify the different gestures. Carpacio achieved an accuracy of 99.4% driver/passenger differentiation across a total of 2600 touches performed on eight vehicles and five mobile devices.

RELATED WORK

Through Body Capacitive Communication

Zimmerman documented the original concept on through body signal transfer using capacitive coupling. Since then a large body of work has emerged focusing on using capacitively coupled systems for information communication [19,20]. Researchers have investigated capacitive coupling characteristics such as the effect of the body's impedance [2,13], coupling surfaces [4], and common grounding effects on signal strength [9]. Various custom systems have been proposed, such as the highspeed system by Bibin Babu's Connected Me [3], and Yoo et al's low power body coupled communication system [18]. Moving away from the use of custom hardware, Hessar et al. demonstrated that commodity capacitive sensors such as the touch screens and finger print readers can also be an effective signal source for through-body communication [10].

Sensing electrical signals coupled to the human body exists beyond data communication. A major advantage to body coupled systems is that the signal only propagates when a body connects the signal source and receiver, providing it as an opportunistic mechanism for identifying who the touch is coming from. Matsushita et al.'s Wearable Key [14] system proposes a wristband that generates a signal encoding a unique user identification code that capacitively couples to the wearer's body. When the user then touches a receiver embedded in the environment, such as on a keyhole, the unique ID is sent through the body for identification. In a similar vein, Holz et al. uses the same wristband concept, but using a capacitive touch screen's built-in sensing capability to capture the coupled signal [11]. In the reverse, Dietz et al.'s DiamondTouch [6] demonstrates that by instrumenting a signal source on a touch area, such a table top, and sensors on the surrounding area where the user are located, such as on each seat, when a user touches the table, the corresponding seat will receive the signal. In this way, users do not have to be instrumented.

Touch Source Discrimination in Vehicles

Discriminating driver and passenger for in vehicle interaction is important for adapting user interfaces for safety and user specific controls. To distinguish where a phone is being used in a vehicle, Yang et al. proposed a multi-source time-of-flight ultrasound location tracking of a smartphone [17]. This method assumes the user of the phone corresponds to the location of the phone. This assumption, however, does not work for the built-in screen in the car, which requires a different set of solutions. Herrmann et al. has integrated an IR camera system on the top of the vehicle roof to track the hand, and distinguish the likely origin of the hand. 3M [8], Cypress [16], and Atmel [12] have all independently proposed a driver passenger discrimination system based on capacitive coupling of electrical signals. Their system instruments each seat with an electrode that injects a high frequency electric signal that capacitively couples to the body. When the seated person touches the screen, this electrical signal is then transferred into the screen, and the screen can act as a sensor to this signal. By sending a different signal through each seat, the screen can discriminate which seated user touched the screen. Carpacio is a more feasible solution as it requires little additional hardware. It eliminates the need for a dedicated signal source in each seat by reusing the screen as the signal source and the heating coil or occupancy sensor can be used as the electrode on the seat.

The same touch source discrimination using single source body capacitive coupling concept is demonstrated by Dietz et al. in Diamond Touch. In their follow-up work, DT Controls [5], Dietz et al. illustrates how the DiamondTouch hardware could be instrumented in the car's touch screen and buttons to differentiate between the driver and passenger. Through distinguishing the touch source, the same touch screen button could illicit a different UI and the same window control button could open and close the windows on the respective side of the car depending on the user. DT Controls mainly focuses on applications that enhance usability in the car. Our work further substantiates the claims made in DT Controls in two ways. First, the custom signal source needed in DT Controls can be omitted in favor of capacitive sensing technology built into modern vehicles' capacitive touch screens, smartphones used in the car, or capacitive buttons for console control. This reuse of existing capacitive sensors is inspired by Hessar et al. Second, we validate the system to demonstrate the quantitative performance in a realistic environment and the necessary signal processing for managing signal noise in modern cars.

METHOD

The Carpacio prototype consists of two resistive heating seat cushions placed on the driver and front passenger seat, one PicoScope digital acquisition device with a differential connection (positive: coils in the cushion, negative: vehicle ground through car socket) with an input impedance of 1 MΩ sampling at 1 MHz for each cushion to avoid aliasing, a laptop to control the data logging, and a ground cable to tie the PicoScope ground to the car ground (Figure 3). We envision that the Carpacio system would ultimately be embedded into a vehicle, either using the existing electrical meshing used in resistively heated seats or capacitive passenger seat pads for occupancy classification.

We chose to use an external seat pad instead of tapping into the existing seats because our main contribution is to examine the performance of this system in a variety of cars rather than fully integrate it into a specific vehicle. Furthermore, the effort to fully integrate this system requires irreversible modification to cars. The general functionality of capacitive touchscreen requires the touch controller to send high frequency signals into the touchscreens via the transmit electrodes (TX).

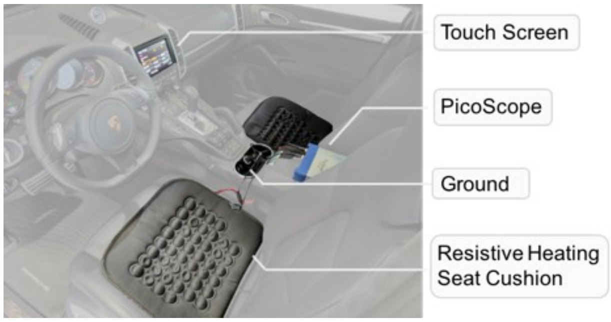

Figure 3: Carpacio data collection setup

When nothing is touching the screen, the signal couples to the receiving electrodes (RX) through the air, however, when a finger encounters the screen, a portion of the current is drawn away from the TX-RX connection and into individual's body. This parasitic signal can be detected using an electrode, such as a mesh of wires contacting the body, if the grounds of the sensing system and the screen are shared. For a phone, that means the phone should be plugged in to the car for Carpacio to reliably detect the signal. Carpacio uses the signal that is grounded through the individual's body as its signal source (Figure 4).

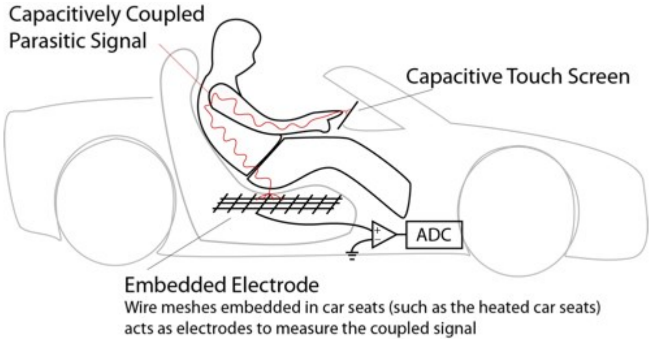

Figure 4: As a user touches the screen, a signal is coupled to the body. By using an electrode embedded in the seat, this signal can be measured using an ADC

A survey of the eight vehicles and five mobile devices shows that most touch sensors uses a frequency of 50 – 400 kHz with a bandwidth between 5 – 20 kHz (Table 1).

To isolate and extract the signal resulting from a touch interaction, a series of signal processing filtering techniques are applied. First, an equiripple bandpass filter is generated and applied to the original signal. This filter parameterized by a screen specific center frequency and bandwidth, along with -80 dB stopband attenuation. In our development, we manually measured the signal for each screen to determine the center frequency and bandwidth of the screen's TX signal. We found that almost all screens had a different center frequency as shown in Table 1. This calibration only takes a 10 second measurement of the baseline noise and a 2 second user touch on the screen. This calibration would be built-in for Carpacio-equipped vehicles, and could be pre-calibrated for various popular phone models through a database of phones and their corresponding touchscreen models. If a calibration stage is necessary, a short calibration routine can be performed. With the touch signal extracted using the bandpass filter, the 1 MHz signal is down-sampled by 100 times to 10 kHz to speedup post-processing. Most signals have a bandwidth between 5 to 20 kHz bandwidth, which after bandpass filtering, allows for reconstruction of the signal even with aliasing. A three-point median filter is applied to the downsampled signal to reduce the effect of sporadic impulse noise created by the sensing signal of the capacitive occupancy classification system (OCS), which is typically a periodic burst [7]. Finally, the magnitude of the signal is calculated by taking the absolute value.

Table 1. Sensing frequency of surveyed cars and phones

Screen Type	**Devices*(Center Frequency in kHz, Bandwidth in kHz)***
Mobile Device	iPhone 5 *(117, 10)*, iPhone 6 *(117, 10)*, Nexus 6P *(208, 10)*, Pixel *(145, 10)*, Galaxy Tab *(262, 10)*
In-Car Touch Screen	Mazda CX5 2017 *(82, 5)*, BMW 740x 2017 *(86, 3)*, VW GTI 2017 *(385, 20)*, VW Tiguan 2017 *(165, 5)*, Mitsubishi Outlander 2017 *(340, 10)*
Capacitive Console Controller	Mini Cooper 2015 *(60, 30)*, Mercedes C300 2017*(120, 20)*

To differentiate the source (driver or passenger) of each touch, a classification is made every time a touch is registered on the screen. This classification is done by calculating the maximum 10 values of the magnitude in a 1.5 second window around the touch event for both driver and passenger seats. The median value of the top 10 values is calculated and compared for both seat signals (red and blue signals in Figure 5). The higher of the two is classified as the user who touched the screen. Our groundtruth timestamps record when the speech-to-text system finishes announcing the touch command. The delay between the command being announced and when the touch lands is not very consistent. This led to the need to use a much wider window for touch classification, which causes the total energy method to be less effective. In a fully integrated system, the Carpacio classification system is queried by the screen after a touch is detected, allowing for a much tighter window that is guaranteed to have a touch, in which case, the typical total energy method would work more reliably. We found this to be true in a prototype implementation of a real-time system.

Occasionally the impulses produced by the capacitive OCS are not removed by the median filter, and could even overpower the actual touch signal. This was observed in only about 5 cases in our 2600 touch dataset. Through some experimentation, we found that the impulses that do remain are effectively removed by using the 10 highest point median solution. We did, however, find that by simply calculating which side had the highest magnitude also worked on more than 99% of the dataset, but missed the few cases where the noise peaked up.

VALIDATION

We evaluated Carpacio's performance at distinguishing between touches by the passenger and driver in a controlled, in-car study. We tested the system in eight different car models at various dealerships, including two cars that use a capacitive controller (Figure 2, Middle) to interact with the screen. In one car, we tested four different phones and one tablet, all mounted near the center console of the vehicle (Figure 2, Right). For each test, the seat pad electrodes were placed on the driver seat and the front passenger seat. The PicoScope data acquisition device is placed on the center armrest, with the laptop positioned in the backseat. For each test, a total of 200 touches are performed, with one touch performed every two seconds. The touches were evenly split between the two users and broken into four different touch categories: tap, tap and hold, swipe, and multi-touch hold. The users were asked to perform each gesture in a natural way. For reference, on

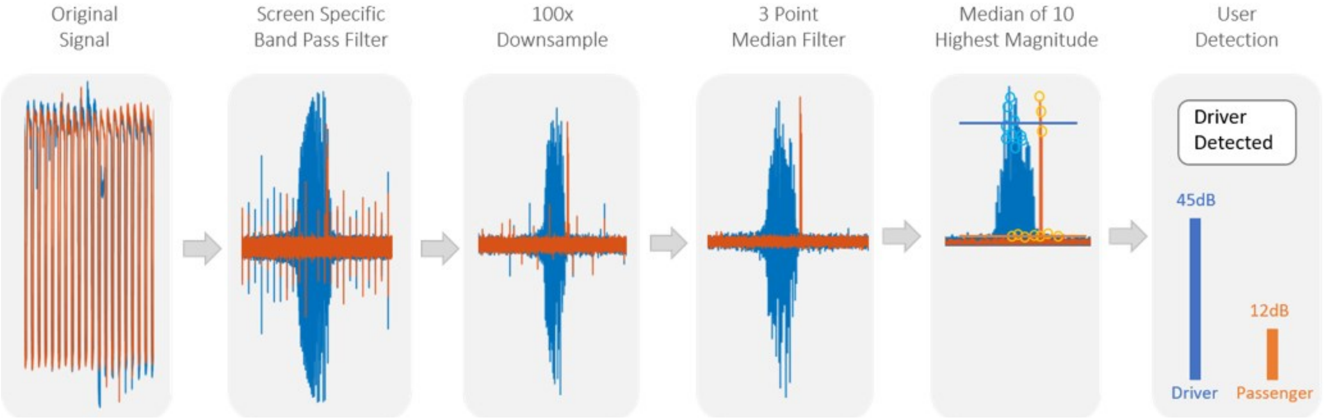

Figure 5: Algorithm diagram. Each block shows a step in the signal processing pipeline. The blue signal is the time domain signal measured by the seat pad on the driver's side. The orange signal is from the passenger's side. The final output of the system is a classification of driver/passenger based on which side has the stronger signal after filtering.

average the users' taps lasted 136 ms and the tap and hold/swipe/multi-touch hold gestures lasted 1150 ms. The experiment makes use of the laptops text to speech system to announce the type of touch, and who is to touch the screen at about two second intervals. Commands are given in a different randomized order each trial and the location of touch is up to the user.

RESULTS

A total of 2,600 touches were collected (1,200 for the six in-car touch screens, 400 for the two capacitive console controllers, and 1000 for the five mobile devices). Carpacio demonstrated robust driver/passenger differentiation at 98.9% accuracy (1187/1200) for touch screen cars, 99.8% accuracy (399/400) for capacitive console controllers, and 99.8% accuracy (998/1000) for mobile devices, for an average accuracy of 99.4% (2584/2600). The decreased accuracy of the six touch screen cars can be attributed to a few factors. In the BMW 740x, when the car first started, an over-powering capacitive probing system activated in the vehicle, drowning out the touch signal (Figure 6, Right). This resulted in five missed touches. Note that this over-powering probing signal stopped after the first five touches. We suspect this to be some form of the vehicle's OCS performing a high-fidelity check right as the car starts. In the remaining eight missed cases, three of the touches showed very low signal-to-noise ratio (Figure 6, Middle). We suspect that this may be due to the user having touched too close to the edge of the screen, leading to a weak coupling. The remaining five touches, after thorough examination showing an obvious signal from the opposite user for each touch, we believe that the wrong user may have touched the screen due to an error in interpreting the text-to-speech command.

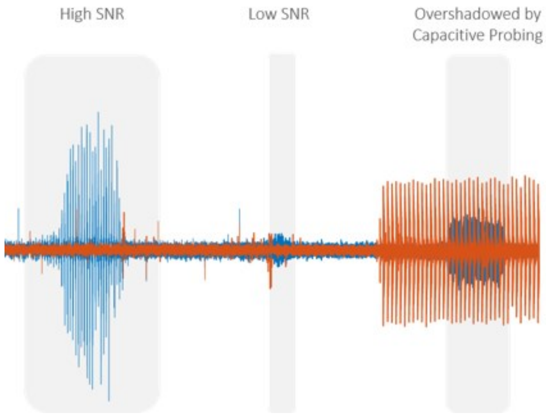

Figure 6: Example of the typical signal which exhibits a high SNR (Left), example of a signal exhibiting a low SNR that cannot be detected (Middle), example of a touch signal overshadowed by capacitive probing of the OCS (Right).

DISCUSSION

Limitation of Carpacio

In the process of developing Carpacio, we have documented a variety of findings that both helped us develop the algorithm of Carpacio and define its limitations. First, as formalized by Grosse-puppendahl et al. in [9], for capacitive coupling between devices to occur, their grounds must be shared. Although this would be the case for the in-car screen and console controller, it is not a guaranteed case for smartphones in the car. When the phone is plugged in to the cigarette socket, its ground is tied to the car, allowing for capacitive coupling to properly occur for our system. If the phone is not plugged in, it was observed that coupling sometimes occurs if the phone is placed on the dash near the middle console, likely due to coupling through the wires in the console. The system does not work at all when a user holds the phone.

Another limitation is not all touch screens in cars are capacitive sensing based. Some cars have resistive touch screens. Of the cars we tested, we also observed interesting situations where there is an observable signal, but it differs from the standard capacitive screen. The screens in the 2017 Chevrolet Corvette, 2015 Chevrolet Corvette, 2015 Porsche Cayenne, and 2013 Jeep Cherokee produces a detectable signal when a user touches the screen. However, the signal is a DC impulse instead of a modulated signal expected of a capacitive touch screen, nor is there no signal, as expected for a resistive touch screen. We chose not to further examine this signal in our evaluation, but it may be possible to develop a specific filter that could be effective for such a screen characteristic.

Lastly, as seen in the missed classification for the 2017 BMW 740X, sometimes the capacitive probing signal used by the OCS is over powering. We also noticed this in the 2013 Chevy Malibu. In the BMW, it was obvious the OCS system went into a high-power mode right when the vehicle starts, but drops after about 10 seconds. This issue is a problem mainly because the OCS frequency and touch screen frequency were very similar. In the Mini Cooper, we noted the OCS frequency was about 200 kHz above the touch sensor frequency. In this case, they did not interfere with each other. For Carpacio to work, the OCS and touch sensor frequency would ideally be further apart in frequency.

Integrating Carpacio into a Car

The prototype data collection system is built from external hardware, but the actual hardware necessary to integrate Carpacio into a new car is minimal. For any car with electric heating in the seats, one ADC can be attached to each seat's heating element to recreate the detection setup. A potential improvement to the current system could be an analog filter, which would reduce the need for embedded processing. Alternatively, since 2006, every car sold in America is required to incorporate an OCS in the passenger seat to determine the size of the passenger for adjusting airbag deployment speeds [15]. Many of these systems use a capacitive sensing system that incorporates a large electrode into the seat or side door of the car. In fact, a 2015 recall made by Subaru for the 2012 Subaru Impreza was caused by interference from the coupled signals of smartphone screens, the same signal that Carpacio measures [1]. Instead of implementing a filter to remove this signal, car manufacturers could instead use this signal.

During the evaluation, we did not collect the exact timing of when the user landed the touch on the screen, but only the timing of when the command was issued by the text-to-speech system. With successive commands issued every 2 s, we chose to use a 1.5 s window to guarantee that the touch event occurred. Although a 1.5 s response time is slower than a typical touch event, we imagine the touch identification in a car does not need to react to every touch. Instead, we imagine the user identification would be particularly useful during interface switching scenarios, such as calling up keyboard or voice input and opening an app in driver or passenger mode. However, it is worth noting the 1.5 s delay is mostly an artifact of the lack of exact touch timing. An integrated system will have touch events from the screen. With the system being able to detect the signals from taps, which is on average about 136ms during our evaluation, the signal is clearly detectable in a much smaller window. By only querying Carpacio when a touch has occurred, the system can keep a rolling buffer of raw signal values and only do a signal strength comparison when queried. We explored this querying method in an online implementation.

Online Implementation

The performance evaluation described in the validation section is conducted using a post processing algorithm developed in MATLAB. We also developed a prototype online implementation in C++ to demonstrate that Carpacio can work in real-time. The hardware setup includes the PicoScope connected to two heated seat pads operating at 500 kHz. We found that the decreased sampling rate was necessary to make the online bandpass filtering perform without delay, and noticed it does not reduce the performance when we tested the system in a few cars. The bandpass filter was limited to 50 coefficients to further guarantee processing speed. Unlike the evaluation setup, the real-time system is connected to the touch screen via a network connection, giving it more direct information about when a touch occurs. When a touch is detected on the screen, the application on the screen queries the Carpacio system for whether the driver or the passenger touched the screen. In this case, in contrast to what we observed in the development of an offline system without exact timing of the touch event, we found that a one second buffer worked very reliably. It should be noted that due to network uncertainties and delays, we were still not able to reduce the buffer further. In a fully integrated system, we believe the buffer can be further reduced. We integrated this system through a browser in a 2015 Tesla P95D and with a tablet used in a 2005 Toyota Matrix. In both cars, the real-time system performed reliably.

Potential Use of Carpacio

The high SNR shown in Figure 7 is typical in most of the cars tested when stationary. In the 2005 Toyota Matrix, we also tested the signal quality when driving and the results are similar and showed no artifacts due to driving. Although we did not test the driving scenario in other vehicles, we believe that it should not be very different. Furthermore, the integrated system would only query Carpacio when a touch event is registered by the touch screen. Thus if there are artifacts that sometimes occur during driving, it would likely not affect the performance. In a similar vein, touch-based queries would also be useful for the system to enable multi-user support. The current system only supports one touch at a time, but the integrated system would check for changes in the signals in the two seats corresponding to touch events. Thus, if users don't simultaneously touch the screen, the system would be able to determine the origin of the touch.

Aside from providing in-car user interface enhancements, Carpacio can also provide useful metrics to the driver, employer, insurance agencies, or automakers. For example, a driver distraction metric could be formulated from logging driver phone and infotainment touch events while the car is in motion. These accumulated touches could have GPS, timestamp, and vehicle speed metadata which could be used for advanced driver metrics. Unlike previously mentioned applications which rely on Carpacio being queried for the touch source as touches occur, this application could autonomously monitor the filtered Carpacio data and accumulate driver touches based on a preset threshold (Figure 7). A downside to this thresholding is the possibility of touches being falsely detected due to noise or a poorly calibrated threshold. Additionally, there is no need to differentiate between which screen is being touched (phone or in-car screen) since any driver touch interaction seen by Carpacio contributes to the driver's distraction. From this, a metric can be defined to output a distraction score based on the timing and quantity of driver touches.

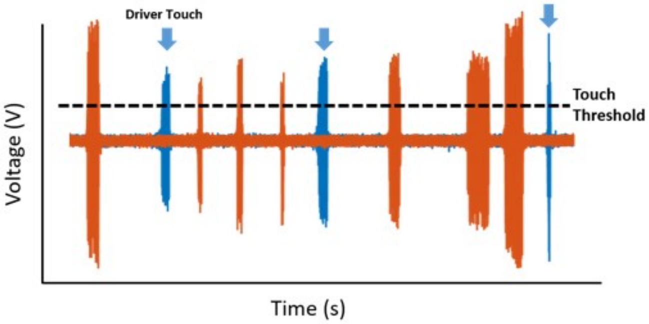

Figure 7: Example showing thresholding for driver touch detection.

CONCLUSION

Using the existing hardware infrastructure in a car, Carpacio enables touch source differentiation between driver and passenger. In an evaluation of eight cars and five mobile devices in a car, Carpacio robustly differentiates touch origins with an average accuracy of 99.4%. Such a system can ultimately be incorporated into cars for adaptive user interfaces, tracking driver distraction, and improve driver assistance technology.

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